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SIGNIFICANT EXPERIENCES OF THE NASA PLUM BROOK REACTOR FACILITY

by H. B. Barkley, Jr.

Lewis Research Center

Cleveland, Ohio

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ABSTRACT

Representative facility oriented and experiment oriented accomplishments of the NASA Plum Brook Reactor Facility at Sandusky, Ohio, are presented. Several significant problems solved are described. To provide a context for understanding the information in the report, a brief description of the facility, its purposes, and the experimental program and environments are included.

SIGNIFICANT EXPERIENCES OF THE NASA PLUM BROOK REACTOR FACILITY*

by H. B. Barkley, Jr.

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SUMMARY

The NASA Plum Brook Reactor Facility (PBRF) at Sandusky, Ohio, consists of a 60-megawatt(t) test reactor; a 100-kilowatt(t) mockup reactor; a seven-cell hot laboratory; chemistry, radiochemistry, electronic, electrical, and metallurgical laboratories; and supporting facilities. The reactor experiments support the application of nuclear power to space for power and propulsion. The need for accurate data is intensified by the space requirement for minimum shielding and maximum lifetime.

Experiment specimens include materials - unfueled and fueled, devices, and complete assemblies such as the NERVA actuators.

Ranges of experiment environments include (1) temperature: 30° R to 5500° F; (2) atmosphere: water, vacuum, liquid metal, and gaseous (air, helium, nitrogen); and (3) nuclear flux (maximum): fast flux ($E > 0.1$ MeV), 2×10^{14} neutrons per square centimeter per second; thermal flux, 10^{15} neutrons per square centimeter per second; gamma heating, 14 watts per gram in water.

Representative accomplishments are described and separated into (1) those facility oriented and (2) those experiment oriented. It is noted that about 1100 irradiations have been safely completed, with 32 active experiments.

Significant problems, which have been encountered and solved, are then described.

It is concluded that the NASA Plum Brook Reactor Facility is maturing into an experienced organization, which is obtaining usable and meaningful data instrumental in the application of nuclear power to space.

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*Presented at American Nuclear Society Conference, Washington, D. C., Nov. 11-16, 1968.

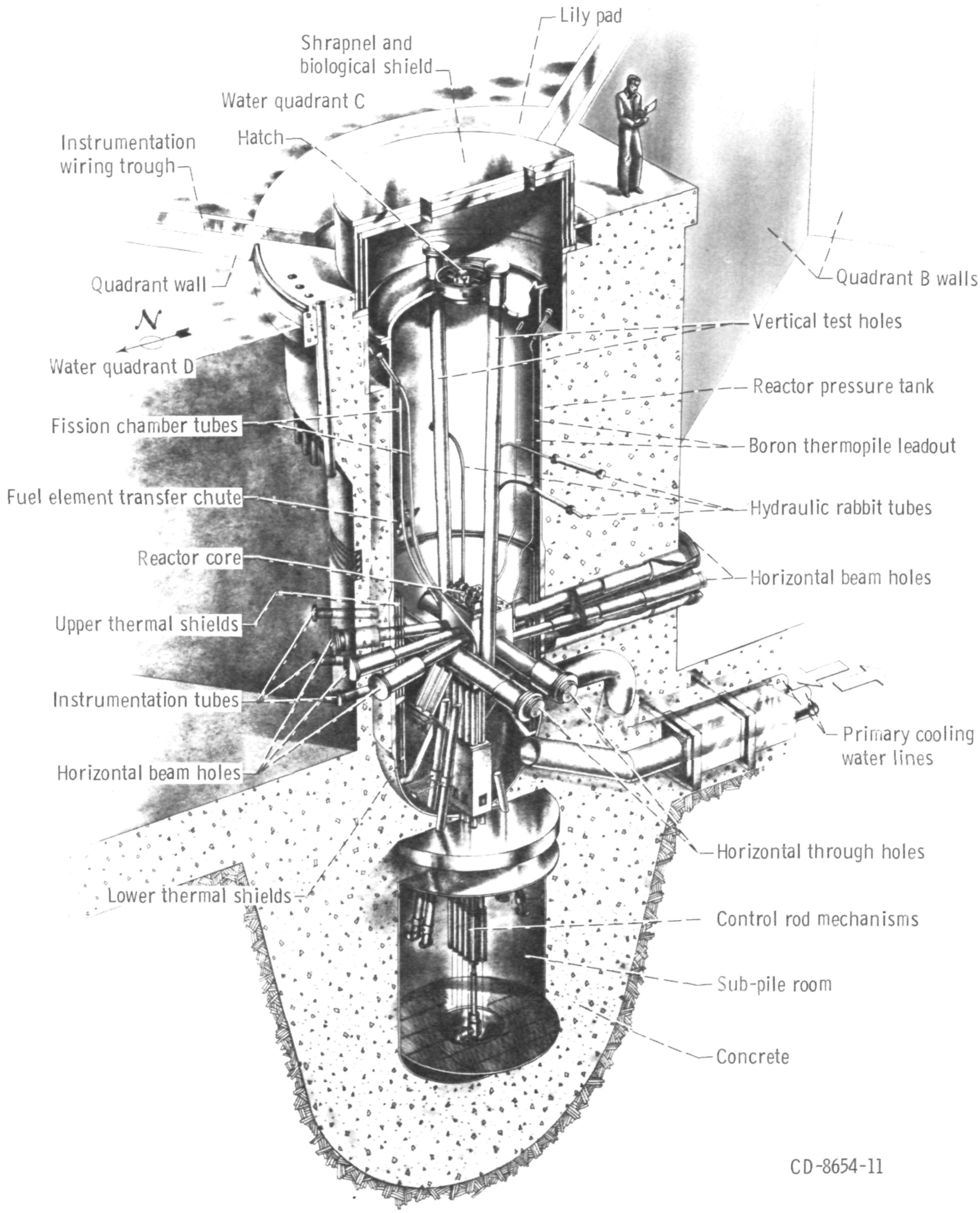
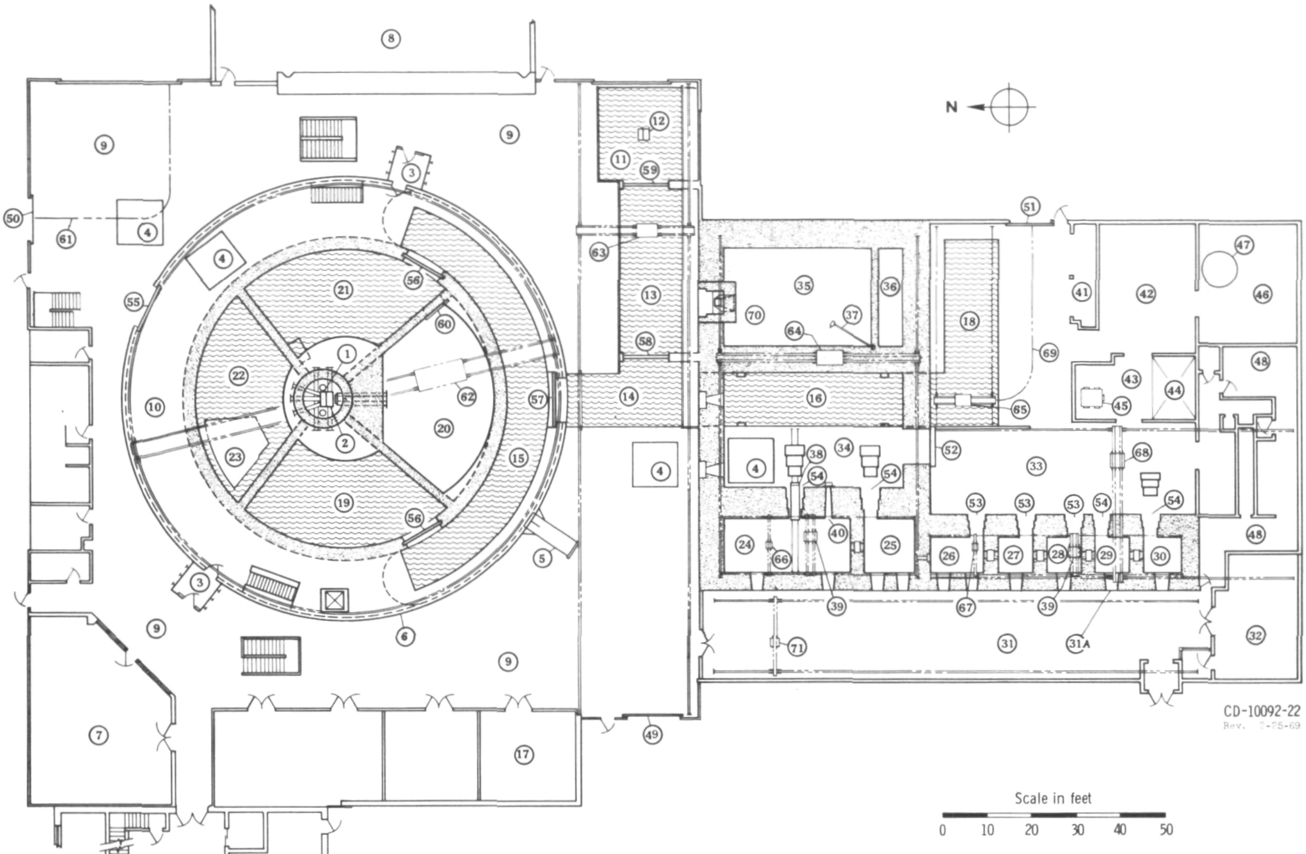


Figure 1. - Cutaway perspective drawing of the Plum Brook Reactor Facility reactor tank assembly.



1 Reactor
2 Reflector
3 Air lock
4 Hatch, 10 by 10 ft
5 Experiment air lock
6 Containment vessel
7 Experiment control room 5
8 Pump house
9 Area 1: elevation, 0 ft 0 in.
10 Area 2: elevation, 0 ft 0 in.
11 Area 3: canal H, 21 ft 0 in. square
12 Area 3: mockup reactor (MUR)
13 Area 3: canal G, 16 ft 6 in. wide
14 Area 3: canal F, floor elevation, 25 ft 0 in.
15 Area 18: canal E, 11 ft 0 in. wide
16 Area 18: canal J, 12 ft 0 in. wide by 40 ft 6 in. long; floor elevation, 25 ft 0 in.
17 Area 4: hot lab office; floor elevation, 0 ft 0 in.
18 Area 20: hot wet storage, 15 ft 0 in. wide by 45 ft 6 in. long; floor elevation, 25 ft 0 in.
19 Area 23: quadrant A; floor elevation, 25 ft 0 in.
20 Area 24: dry quadrant B; floor elevation, 27 ft 0 in.
21 Area 25: quadrant C; floor elevation, 25 ft 0 in.
22 Area 26: quadrant D; floor elevation, 25 ft 0 in.
23 Area 26: underwater beam room facility
24 Room 1: hot cell area
25 Room 2: hot cell area
26 Room 3: hot cell area
27 Room 4: hot cell area
28 Room 5: hot cell area
29 Room 6: hot cell area
30 Room 7: hot cell area
31 Room 8: hot cell area; control room and work area; floor elevation, 0 ft 0 in.
31A Master-slave manipulators at all windows, periscope plugs at each cell
32 Room 9: manipulator repair area
33 Room 16: semicontaminated work area, 20 ft 3 in. by 62 ft 6 in.
34 Room 17: hot handling, 15 ft 9 in.
35 Room 19: hot dry storage, 27 ft 3 in. by 32 ft 6 in.; floor elevation, 25 ft 0 in. (concrete slab cover not shown)
36 Room 19A: off gas system
37 TV boom
38 Transfer cart
39 General Mills model E-2
40 Cutoff hole
41 Room 21: storage
42 Room 22: repair shop
43 Room 23: decontamination
44 Hood
45 Glove box
46 Room 24: storage
47 Sample storage well
48 Lockers

Doors and openings:

49 D-1
50 D-2
51 D-10
52 D-10
53 D-11
54 D-12
55 D-13
56 D-16
57 D-17
58 D-20
58 D-19
59 D-20
60 D-21

Cranes and hoists:

61 5-Ton hoist
62 20-Ton crane
63 20-Ton crane
64 20-Ton crane and 5-ton hoist
65 5-Ton crane
66 1-Ton crane
67 1-Ton crane
68 15-Ton crane
69 5-Ton hoist, electric
70 2-Ton crane below
71 1-Ton crane, hand operated

Figure 2. - Plan view of reactor and hot laboratory buildings.

INTRODUCTION

A brief description of the NASA Plum Brook Reactor Facility (PBRF) at Sandusky, Ohio and a statement of its purposes are necessary to provide a context for understanding its significant experiences and accomplishments presented in this report.

The Reactor Facility consists of a 60-megawatt(t) test reactor; a 100-kilowatt(t) mockup reactor; a seven-cell hot laboratory; chemistry, radiochemistry, electronic, electrical, and metallurgical laboratories; and supporting facilities. A cutaway view of the 60-megawatt(t) test reactor is shown in figure 1. The mockup reactor is nuclearly identical to the 60-megawatt test reactor. It is used for (1) reactivity, flux, and power distribution measurements for various core loadings and configurations; (2) measurement of unperturbed and perturbed experiment fluxes (neutron and gamma); and (3) measurements of experiment reactivities. These measurements permit efficient operation of the 60-megawatt test reactor to provide desired, accurately known environmental conditions. The other laboratories and facilities enable fulfillment of the basic purposes of the Reactor Facility. Figure 2 is a plan view of the reactor and hot laboratory buildings.

The purposes of the Reactor Facility are to determine three things for specimens in a nuclear radiation environment: (1) their tolerance to radiation, (2) the nature and cause of their radiation induced changes, and (3) how to increase their radiation tolerance. The reactor experiments support the application of nuclear power to space for power and propulsion. Space oriented experiments intensify the need for accurate data, because the application dictates minimum shielding and maximum lifetime.

The following sections will briefly describe the scope of the experimental programs conducted at PBRF, summarize representative facility oriented and experiment oriented accomplishments, and then briefly discuss several significant problems which have been encountered and solved.

EXPERIMENTAL PROGRAM

The types of experiment specimens irradiated are shown in the following tabulation:

MATERIALS
Unfueled: Structural Insulating Lubricating Shielding Activation Tektites Crystals . Fueled: Thermionic fuel forms High temperature reactor fuel forms
DEVICES
Semiconductors Thermionic diodes Transducers Diffraction crystals Spectrometer
COMPLETE ASSEMBLIES
NERVA actuator

EXPERIMENT ENVIRONMENTS

The ranges of environments used for in-pile experiments are summarized in the following tabulation:

Temperature . . . . 30° R to 5500° F
Atmosphere . . . . Water, vacuum, liquid metal, gaseous (air, helium, nitrogen)
Pressure . . . . Vacuum to 2000 psi
Nuclear fluxes (maximum):
Fast flux ($E > 0.1$ MeV) . . . . 2×10^{14} n/cm^2/sec
Thermal flux . . . . 10^{15} n/cm^2/sec
Gamma heating . . . . 14 W/g in water

ACCOMPLISHMENTS

Representative accomplishments of PBRF may be separated into (1) those facility oriented and (2) those experiment oriented. In describing these accomplishments, the attempt is to give only enough detail to indicate the significance and the general method of achievement. Additional detailed information on any of these items is available from the author.

Facility Accomplishments

The original design for the Plum Brook Reactor (PBR) used a core loading of all new 168-gram U^{235} MTR-type fuel elements. These elements were to be replaced each cycle. We have evolved to a zone loaded core, using triple-cycle 240-gram U^{235} fuel elements. By increasing the uranium loading in each element, zone loading the core, and using each element for several cycles, we achieve maximum burnups of about 60 atomic percent U^{235}, longer cycles at high power, and major reductions in fuel costs.

Each reactor cycle requires a new fuel loading to be determined, using some new elements and many elements partly depleted to varying degrees. Calculations of charge life, critical control rod position, and power distribution are required for each reloading. For the triple zone core, this evolution is performed in about 1 hour, using an IBM 1620 computer. There is a corollary gain in that all necessary special nuclear material accountability information is also obtained.

By careful measurement of reactor power distributions and refinements in our methods of heat transfer analysis, including statistical combination of uncertainties, we are able to go to full reactor power of 60 megawatts with our mixed fuel loadings at the start of our 15-day full core life.

By careful attention to plant and experiment problems, we have improved plant reliability and maintainability and thereby continue to reduce cutbacks from all causes. In 1965, there were 37 cutbacks; in 1967, there were 19 cutbacks, with only six irrecoverable scrams where xenon prevented restart.

The Reactor now can generate 90 percent of the maximum possible megawatt days (MWD) per month, except when it is down for major experiment installations or modifications. Experiment shutdowns have been reduced to a minimum, since installation of most major experiment facilities has been completed. Our capability of high on-line time is a result of the improved plant reliability and maintainability mentioned above and a substantial reduction in the refueling time.

We have reduced costs for radioactive waste disposal by about \$30 000 per year despite major increases in the amount of waste. This primarily resulted from development of reusable containers for these disposals.

During the past several years, we have devoted considerable attention and effort to training technicians in the operation of the reactor, reactor systems, and experiments. Engineers have been replaced with technicians in the following key positions: Senior Reactor Operator, Reactor Operator, Experiment Supervisor, and Service Supervisor. This has freed engineers to concentrate on difficult experiments.

We have designed and developed and are using a nitrogen-17 fission product monitor. This system uses two neutron detectors spaced about two nitrogen-17 half lives apart in the primary system. In a clean system these detectors see primarily neutrons from nitrogen-17. The ratio of the signals from these two detectors is taken and is constant for all reactor powers. Delayed neutrons from fission products, however, cause a drop in the ratio. Thus the presence of nitrogen-17, which normally produces an undesired background for delayed neutron detection, is used to advantage to give a constant indication that the system is operable. The system responds sensitively and rapidly to the delayed neutrons of fresh fission products. Further, the ratio can be calibrated in terms of "steady-state" levels of other fission products of interest.

Hardware and containment facilities have been built in the hot laboratory to permit processing fueled experiments within 1 day after irradiation. The gas puncturing, sampling, and analysis rigs permit rapid diagnosis of the integrity of fueled specimens. The double containment facilities permit disassembly and examination of the fueled specimens.

Experiment Accomplishments

A number of experiment facilities have been installed which permit insertion and removal of experiments during reactor operation, remote positioning of experiments, and control of the temperature and atmospheric environment of experiment specimens. For example, figure 3 shows an experiment insertion machine located in one of the normally water-filled quadrants surrounding the reactor tank. This machine can insert the large (9-in. diameter by 15-ft length) capsule shown, and other similar capsules, through a seal and valve assembly into the reactor during full power operation. It can also position the experiment to obtain the desired fluxes and/or temperature. A capsule similar to the one shown is part of one of three cryogenic facilities, which provide a total cooling capacity of about 40 kilowatts at 50° R. The cryogenic capsule permits the irradiation of either a large specimen or many small specimens in high fluxes at cryogenic temperatures. Figure 4 is a picture of a simple high temperature loop developed by Lewis Research Center. This loop permits irradiation of fueled specimens at temperatures up to several thousand degrees Fahrenheit. Recirculating helium can transfer up to 30 kilowatts from the fueled specimen to the primary cooling water.

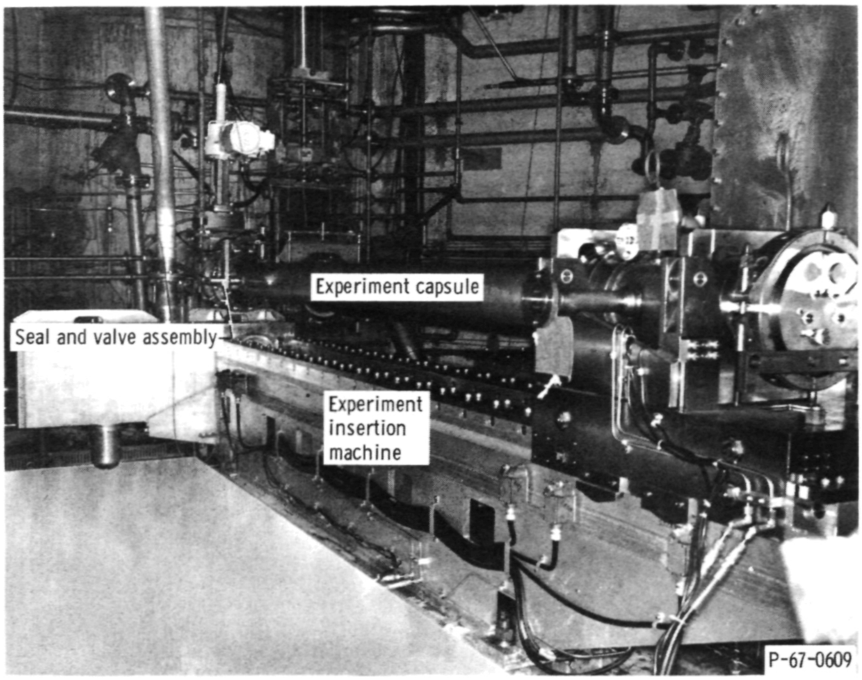


Figure 3. - Experiment insertion machine.

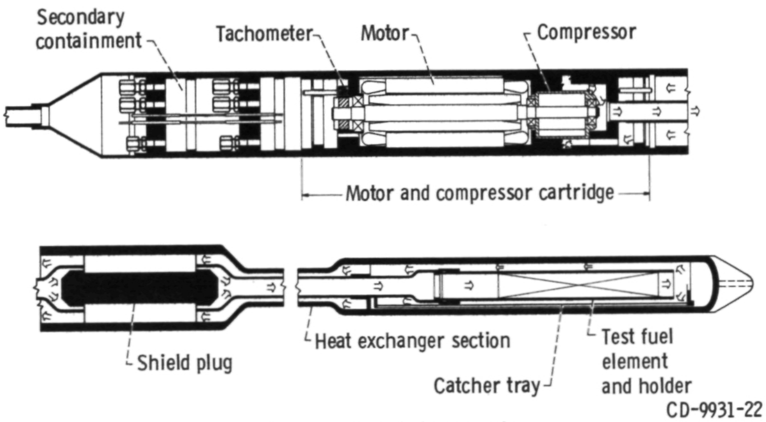


Figure 4. - Circulating capsule.

We have developed experiment envelopes and analyses to simplify the use of each of the experiment facilities. The experiment envelopes describe the operating and safety limits of the experiment facilities. We or an experimenter can readily determine if any experiment facility meets the needs of a particular experiment or if it can be simply adapted. Analyses have been done for these envelopes so that relatively little effort is now required to install an experiment in the facility for irradiation.

There is also now available a myriad of standard equipment which we have found to give satisfactory service. The use of standard equipment in any experiment, of course, reduces the design effort required and provides further assurance of reliable operation. Examples of standard equipment are: experiment lead tubes, experiment positioning de-

vices, standard ASTM specimen irradiation capsule, reactor tank and containment vessel penetrations, thermocouple connectors, underwater electrical devices.

We have issued an Experiment Standards Guide to provide experimenters with concise details for designing and preparing better experiments more easily. The guide consists of eight sections ranging from design and standards for instruments and control systems to design of mechanical devices. There are sections which cover nuclear analysis, heat transfer, fluid flow, radiochemistry and activation analysis, materials selection, electrical design, and postirradiation testing.

Of particular importance to an experimenter is a section of the Experiment Standards Guide devoted to determination of the experiment environment. Most existing radiation effects data from different sources appear to show wide discrepancies and are frequently difficult to correlate. One of the major reasons for the discrepancies is that the experiment environment is not adequately determined. We have adopted a standard method of defining, measuring, and reporting the total experiment environment. This includes the physical environment (e.g., temperatures, pressures, flows) and the complete nuclear environment (neutron fluxes and spectra and gamma energy deposition). All our methods and assumptions are explained in detail. While one may argue whether the selected standard is best, the completeness of the treatment permits anyone to understand what has been done and convert it to any other form that he prefers.

We have devoted considerable effort to make our nuclear flux measurements complete, detailed, and accurate. The flux is determined from measurements in the Plum Brook Reactor and in the Mockup Reactor (MUR). From measurements in the MUR we can provide PBR 60-megawatt-flux information at the 95-percent confidence (2σ) level as follows: thermal flux, ±16 percent; fast flux (energy > effective threshold), ±17 percent; and primary gamma heating, ±19 percent. Uncertainties are reported at the 95-percent confidence (2σ) level rather than as probable error (50-percent confidence) in order to have a high probability that limiting conditions on expensive experiments are not exceeded. Probable error uncertainties would be one-third of values quoted.

We have convinced all experimenters to make an appraisal of the probable magnitude of the uncertainties in the measured and calculated values of their experimental parameters. This is, of course, essential in any experiment to (1) ensure enough adjustment capability is built in to achieve the actual conditions desired, (2) permit a rational assessment of the "operability" of instrumentation, and (3) establish the accuracy of the data.

Many experiments need safety instrumentation to protect against failures that can damage the experiment, the Reactor Facility, or personnel. We have designed standard safety instrumentation systems to measure the more common types of parameters associated with maintaining an experiment in a safe mode, for example: coolant flow, temperature, and radiation levels. These total systems are provided to the experimenter. If a sensor is an integral part of an experiment, it is installed at the time of fabrication of the experiment. The rest of the hardware is permanently installed at the Reactor

Facility. This approach simplifies the experimenter's job. It also reduces shutdowns from experiments and increases our confidence in the equipment because we know it to be standard and reliable. These channels are also eminently suitable for data information.

Most experimental data are recorded on the Experiment Data Logging and Alarm System. This device can monitor 300 channels of information, signal an off-normal condition on any channel, and reduce most raw data to standard units. Typed printouts are available at monitoring intervals as short as 1 minute. Thus the need is minimized for special instruments for experiment data acquisition.

Special flux facilities have been identified and mapped and are available to allow determination of effects of neutron spectrum and neutron to gamma ratio on irradiation experiments. Facilities are available with a high fast to thermal neutron flux ratio, a high fast neutron flux to gamma ratio, a high thermal to fast neutron flux ratio, and a high gamma field (no neutrons).

We have developed a replaceable and retractable thermocouple to solve the problems of long term (thousands of hours) in-pile temperature measurements at 1400° to 2000° C. Most thermocouples that have been used to date to measure in this range have had a short life and questionable accuracy, even at the beginning of the irradiation. Irradiation induced changes have not been well established for the thermocouples, or for the parameters relating the thermocouple reading to the temperature of interest for "indirect" temperature measurements. The replaceable and retractable thermocouple normally resides in a relatively low temperature and reduced flux region and can be remotely inserted into the experiment to read the desired temperature. Thus radiation induced changes and operation at high temperatures are minimized. If the thermocouple fails or drifts, the entire assembly is capable of rather easy replacement. Although the first long time in-pile operation of this device is just beginning, testing to date gives us high confidence in its success.

We conduct a sound review of the programs and hardware for proposed experiments. This has proven effective in enabling the experimenter to obtain the data he really desires. There is a large variation in experience of experimenters in conducting irradiation experiments. The PBRF staff has proven an effective focal point for collection and dissemination of successful techniques for a wide variety of radiation experiments.

Selection of an experiment facility and conceptual design of an experiment usually require knowledge of the approximate nuclear fluxes in the experiment. Starting with unperturbed fluxes in the experiment facility, one then needs approximate values for the perturbing and depressing effects of the unfueled and fueled materials in the experiment. Our catalog of measurements to date provides this information for a variety of materials in most of the experiment facilities. For the high flux test positions, reference 1 provides a handy analytic method, based on experimental results, to predict thermal neutron flux perturbation effects in cylinders.

We have conducted measurements and analyses of the absorption of gamma rays in

various materials. Of particular interest is the absorption in heavy materials, since many heavy, refractory materials are used in high temperature experiments. Failure to account for the much higher gamma absorption (W/g) in heavy materials than in water can lead to significant departures of the experiment from the desired operating temperatures. The Experiment Standards Guide provides values that give good results. Further, reference 2 provides an analytical method for calculating gamma absorption in heavy elements, including the increase in relative absorption as the thickness of the material is decreased.

The most objective measure of our experimental accomplishments is the fact that at the conclusion of reactor operating cycle 75, which ended in February 1968, we had safely completed 1040 irradiations. There are presently 32 active experiments.

SIGNIFICANT PROBLEMS

Of the various problems that have been solved, those summarized in the following paragraphs appear to be of most significance and interest. Sources of additional detail are noted in the text.

Beryllium is used in the PBR control rods, reflector, and core box walls. Detailed surveillance and measurement of each of these components identified that the beryllium was swelling and bowing, because of helium formation at different rates through the components, and was becoming embrittled. In the case of the control rods, the bowing manifested itself in a measurable increase in the rod drop times. That difficulty was corrected by taking the beryllium sections of the rods to the hot laboratory and carefully machining the ends parallel to each other. This decreased the bow in the overall rod, which is made up of three sections, even though it did not change the bow in the beryllium section. A Beryllium Management Plan was developed for rotating control rod and reflector beryllium pieces to prolong the useful life before replacement. In the case of the core box walls, one wall eventually cracked, as had been anticipated. Because the irradiation behavior of beryllium was unknown at the time the reactor was constructed, the core box walls had not been made to be removed. Removal of the core box walls, using electric discharge machining, and replacement were an interesting evolution. The new beryllium was designed with dimensions to minimize (but not eliminate) the effects of long term swelling and bowing, and was made replaceable. The details of this experience, as well as a complete history of the "beryllium problem," are given in reference 3.

In November 1966, the Plum Brook Reactor experienced a temporary loss of forced cooling flow. This event occurred after about 7 days of operation at full power of 60 megawatts(t) when the breaker supplying dc control power to the primary main and shutdown pump breakers was accidentally opened. An automatic pump interlock scram occurred within 1 second after the breaker was opened. Flow coastdown persisted for at

least 30 seconds. Forced cooling flow was restored within an additional 45 seconds. A thorough evaluation, including significant analyses and inspections of the primary cooling water, the core, reactor components, and experiments, confirmed that no damage had occurred. As a result of this event, we reviewed the facility design of critical systems and components. Several modifications resulted from this review. The circumstances and potential consequences of this occurrence were discussed with all reactor operators, and additional operator training and drills on emergency actions on loss of flow were provided. If there is further interest in details of this occurrence or the analyses and inspections conducted, the author will provide the information on request.

The containment vessel of the PBR has a free volume of about 450 000 cubic feet. The Reactor operating license prescribes that the maximum leakage from the containment vessel must not exceed 0.1 percent per day of the contained volume at the overpressure calculated for the maximum credible accident. Early in the operation it was determined that a maximum contributor to the allowed leakage was electrical penetrations. There are about 80 sets of electrical penetrations, including instrumentation and control loads, coaxial cables, and electrical power cables. Although the electrical penetrations were potted or sealed at two points with the volume between monitored by a vacuum system, leakage was found to occur between wires and their sheaths or up stranded cables. We developed a method of applying commercial hermetic seals for the containment vessel penetrations for instrumentation, control, and coaxial cables. Single, unmonitored hermetic seals are used, and they are now tested in place once a year. A double seal is still used for electrical power penetrations. These changes have reduced the leakage through the electrical penetrations to less than 1 percent of the total allowed leakage. Necessary maintenance of the penetrations has been considerably reduced, and flexibility for changes and ease of installation of electrical leads much improved. Our experience with electrical penetrations and detailed descriptions of the specific kinds are given in reference 4.

In April 1967, during a routine, prestart, rod drop time measurement, we detected an increase in the drop time of some of the control rods. The cause of this increase was tracked to wear of some of the support tabs on the lower side of the upper core grid. The upper core grid is a 4-inch-thick piece of aluminum which has rollers on the top to guide the control rods and support tabs on the bottom to hold down and position the fuel elements in the core. Wear of these tabs permitted just enough movement of a few fuel elements for them to interfere slightly with the free fall of the control rods. By removing the stainless steel lifting eyes and control rod roller guide blocks from the aluminum grid, we reduced its radiation level on contact from 250 to 50 roentgens per hour. Lead shot then reduced the radiation level sufficiently that with careful planning, dry run of the repair, and close control and timing by health-physics personnel, the grid could be repaired outside the hot cells. The repair consisted of machining off all of the worn aluminum tabs, drilling and tapping holes in the aluminum grid, and attaching new stainless steel tabs with body fit bolts. The new tabs were positioned within 3 mils of the location

of the old tabs. Subsequent rod drop time measurements confirmed the effectiveness of the repair. A detailed description of the above experience is available from Richard C. Westhoven of Plum Brook.

All of the water leaving PBRF must meet the limits of 10 CFR Part 20. Therefore, all water discharged from the reactor, quadrants and canals, hot laboratory, cooling tower, and even ground runoff, is discharged at one point through our Water Effluent Monitoring Station. To guard against any accidental high activity release, all discharged water is continuously sampled and monitored; and isolation gates automatically close on high activity. Even for analyzed waters (i.e., certain isotopes known not to be present), the activity limits require a monitor with very high sensitivity. Our original system provided protection, but also required considerable maintenance and frequent decontamination, and produced a number of spurious gate closures. We replaced the original system, which used GM tubes, with a new system using scintillation crystals mounted over a 30-inch-diameter soup kettle. A constant level of flowing sample water is maintained in the soup kettle. The detector is shielded with 2 inches of lead from all radiation not originating in the sample volume. The water between the kettle walls and the detector attenuates the effects of radioactive buildup on the walls. By using three photomultipliers with the scintillators and coincident logic, false closures are minimized. Various fail-safe features are incorporated in the control equipment. The system has been effective in minimizing contamination buildup. It has proven stable and reliable at our normal set point of 10^{-5} microcurie per milliliter.

CONCLUSIONS

Less than 5 years ago the Plum Brook Reactor Facility had an operating reactor but essentially no facilities in which to handle or run experiments or control environment. Numerous problems have been encountered and solved, and a few of the most interesting ones are described in this report. Considerable experience and capability have been developed in the difficult area of irradiation experiments. The NASA Plum Brook Reactor Facility is maturing into an experienced facility and organization which is obtaining usable and meaningful data instrumental in the application of nuclear power to space.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 4, 1969,
120-27-05-10-22.

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NASA-Langley, 1969 —— 22 E-4724

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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